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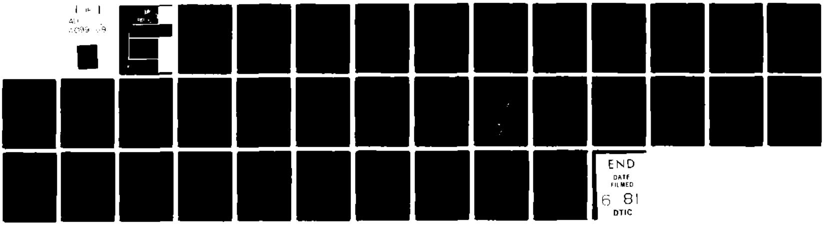

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LIFT-PROPULSION SYSTEM WEIGHT VARIATION FOR
VERY HEAVY LIFT HELICOPTERS

by

Peter S. Montana

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AVIATION AND SURFACE EFFECTS DEPARTMENT

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The lift-propulsion system (LPS) weights of single and tandem rotor shaft-driven helicopters and single rotor tip-driven helicopters were estimated using weight trend equations for vehicle gross weights up to 250,000 lb (113,636 kg). The tip-driven helicopter configuration had the lowest LPS weight over the entire gross weight range and the greatest

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NOTATION

A_R	Engine bypass area ratio
B	Rotor tip loss factor
b	Number of blades per main rotor
b_T	Number of tail rotor blades
C_P	Main rotor power coefficient, $P/\rho\pi R^2 V_T^{\ 3}$
C_Q	Main rotor torque coefficient, $Q/\rho\pi R^3 V_T^{\ 2}$
C_T	Main rotor thrust coefficient, $T/\rho\pi R^2 V_T^{\ 2}$
D_{ET}	Engine turbine diameter, in. (cm)
DIVDIA	Engine diverter valve diameter, in. (cm)
DL	Main rotor disc loading, lb/ft^2 (N/m^2)
D_v	Fuselage vertical drag, lb (N)
d	Tail rotor shaft location with respect to the main rotor shaft, ft (m)
HP	Single engine power, hp
P	Main rotor power, ft-lb/sec (KW)
P_E	Maximum power per engine, hp
Q	Main rotor torque, ft-lb (Nm)
R	Main rotor diameter, ft (m)
R_T	Tail rotor diameter, ft (m)
T	Main rotor thrust, lb (N)
T_T	Tail rotor thrust, lb (N)
$(t/c)_{0.25R}$	Main rotor blade thickness ratio at the 0.25 radius station
V_{ET}	Engine turbine tip speed, ft/sec (m/s)
V_T	Main rotor tip speed, ft/sec (m/s)

V_{TT}	Tail rotor tip speed, ft/sec (m/s)
W	Vehicle gross weight, lb (N)
W_E	Engine weight, lb (N)
X_{NE}	Engine output shaft speed, rpm
X_{NR}	Main rotor shaft speed, rpm
δ	Main rotor blade profile drag coefficient
δ_T	Tail rotor blade profile drag coefficient
ε	Main rotor blade attachment offset ratio
ε_T	Tail rotor blade attachment offset ratio
ζ	Tail rotor location parameter
ρ	Air density, slug/ft^3 (kg/m^3)
σ	Main rotor solidity
σ_T	Tail rotor solidity

ABSTRACT

The lift-propulsion system (LPS) weights of single and tandem rotor shaft-driven helicopters and single rotor tip-driven helicopters were estimated using weight trend equations for vehicle gross weights up to 250,000 lb (113,636 kg). The tip-driven helicopter configuration had the lowest LPS weight over the entire gross weight range and the greatest potential for achieving useful loads in excess of 60,000 lb (27,216 kg). Results of the sensitivity analysis indicate that disc loading, number of blades, and solidity of the main rotor are the most significant parameters affecting LPS weight. The application of circulation control rotor technology to very large helicopters with tip-driven rotors can reduce LPS weight by as much as 19 percent.

ADMINISTRATIVE INFORMATION

The work presented herein was conducted for the Naval Material Command as part of the David Taylor Naval Ship Research and Development Center (DTNSRDC) independent exploratory development program under Project Element 62766N, Task Area ZF66412001, and Work Unit 1-1605-400.

Data are presented in both U.S. customary and metric units. The equations presented were derived in U.S. customary units, and conversion factors must be applied in many cases if metric units are used.

INTRODUCTION

One of the fundamental problems associated with very large helicopters is that the torque required to turn the rotor increases disproportionately faster than the vehicle weight as vehicle size increases. Because transmission weight is proportional to rotor torque, the transmission weight also increases faster than vehicle weight. In addition to being heavy, large transmissions present difficult material design problems and are costly to construct.

One way to partially alleviate the problem of transmission weight increase is to use multiple lifting rotors. An easily derived relationship for transmission weight fraction (assuming constant disc loading) is:

$$\frac{\text{Transmission Weight}}{\text{Vehicle Gross Weight}} \propto \sqrt{\frac{\text{Vehicle Gross Weight}}{\text{Number of Rotors}}}$$

This relation can be used to show that a tandem rotor helicopter could have a 30-percent transmission weight savings over a single rotor helicopter of the same gross weight. Of course, this weight savings cannot be fully realized because of the additional weight necessary for intermediate gear boxes and shafting.

The most obvious way to reduce transmission weight is to eliminate the transmission altogether, which may be accomplished by having the rotor react directly to forces acting at the blade tips. An added benefit of tip drive is that the need for an anti-torque device, e.g., tail rotor, is also eliminated. Without a transmission, a tip-driven helicopter would have the potential for lower empty weight and, hence, a higher useful load than a shaft-driven helicopter. Figure 1 illustrates this by comparing actual and proposed tip and shaft-driven helicopters. As shown in the figure, tip drive is the most promising means of achieving useful loads greater than 60,000 lb (27,216 kg).

This report presents the results of an investigation to determine the relative weights of the lift-propulsion system (LPS) of three helicopter configurations: shaft-driven single rotor, shaft-driven tandem rotor, and tip-driven single rotor. This investigation was conducted as part of the Tip Jet Very Heavy Lift Helicopter Project which was established to assess the potential of combining tip-jet rotor drive with circulation control (CC) airfoils.

The specific type of tip-drive propulsion considered in this investigation is the warm cycle concept in which the exhaust and fan flows from low by-pass

ratio turbofan engines are ducted through the rotor blades and exhausted at the blade tips to turn the rotor.[1*] The incorporation of circulation control[2] would provide the additional benefits of high thrust capability and low vibrations and would further simplify the rotor system by eliminating the need for blade mechanical cyclic pitch actuators. The thick CC airfoil sections provide ample duct area for tip-jet gas flows which will increase the efficiency of the tip-drive system. (See Figure 2 for a comparison of CC tip drive and shaft drive single rotor configurations.)

LIFT PROPULSION SYSTEM WEIGHT PREDICTION

In the early design stages, weight trend equations are frequently used to estimate weights until more detailed design studies can be conducted. This approach was used to develop the comparisons of the three rotor system types in this investigation. The LPS weight trend equations were developed by Boeing Vertol[3] and Hughes Aircraft.[**]

The LPS includes the following components: main rotor blades, main rotor hub and hinges, blade folding mechanism, main rotor controls, main rotor drive system, tail rotor, tail rotor drive system, engines, and engine mounts. The Boeing Vertol equations were used for both shaft-drive configurations and for some of the tip-drive components. The Hughes Aircraft equations were used for the following tip-drive components (for which the Boeing Vertol equations did not apply): main rotor blades, main rotor hub and hinges, and main rotor drive system.

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*A complete listing of references is given on page 13.

**As given in a Hughes Aircraft report of higher classification.

Modifications were made to the trend equations to reduce the number of required independent variables by combining terms and making some configuration assumptions. The independent variables required as inputs for the modified trend equations are listed in Table 1.

ASSUMPTIONS

The assumptions made to modify the trend equations are:

1. Main rotor power was computed assuming hover conditions using the following equations from References 4 and 5:

$$T = W = C_T \rho \pi R^2 V_T^{\,2}$$

$$C_Q = C_P = 0.7071 \frac{C_T^{\,1.5}}{B} + 0.125\ \sigma\delta$$

where

$$B = 1 - \sqrt{2C_T}/b$$

and

$$D_v = 0.06W$$

thus,

$$P = C_P \rho \pi R^2 V_T^{\,3}$$

A 5-percent margin of main rotor power was added to provide for acceleration from hover. Differences in drive system efficiency between tip drive and shaft drive were accounted for by multipling shaft power by 1.66 to obtain tip-drive power.[6]

2. Tail rotor power was computed using the same basic equations for main rotor power plus:

$$T_T = Q/d$$

where

$$Q = C_Q \rho \pi R^3 V_T^2$$

and

$$d = R + \zeta R_T$$

The tail rotor location is shown in Figure 3.

A maneuver margin of 40 percent was added to the computed tail rotor power, and it was assumed that tip drive required one-third of the tail rotor power of an equivalent shaft driven rotor.

3. Engine weights and sizes were computed from trend equations developed from data reported in References 7 and 8; see Figures 4 and 5.

$$W_E = 3.3656\ HP^{0.64444}$$

$$D_{ET} = 0.54753\ HP^{0.43379}$$

Fan engine weight was assumed to be 10 percent higher than shaft engine weight.

4. Drive system weights were computed using an input engine rpm (X_{NE}) or a computed engine rpm for shaft engines:

$$V_{ET} = 1260$$

$$X_{NE} = 720\ V_{ET}/(\pi D_{ET})$$

$$Z = 0.04\ X_{NE}/X_{NR}$$

and for fan engines,

$$DIVDIA = D_{ET}\sqrt{1 + 0.88889\ A_R}$$

CORRELATION

The resulting LPS equations were correlated against known LPS weight from References 3 and 9 and other sources.* A comparison of the known weights and the computed weights is shown in Figure 6. The correlation with shaft-driven LPS weights is very good, while tip-driven LPS weights are somewhat over-predicted at the higher vehicle gross weights. The results of the subsequently conducted parametric analysis are not unreasonably optimistic in that the simulation yields conservative weight predictions for tip-driven lift propulsion systems, which are

*As given in a Hughes Aircraft report of higher classification. (The XV-9A LPS weight was obtained via telephone from Hughes Helicopters.)

relatively unknown compared with shaft-driven lift propulsion systems.

PARAMETER VARIATION

A series of LPS weight estimations was made to evaluate the relative merit of the three LPS configurations and the sensitivity of each configuration to the independent variables. The baseline design parameters are given in Table 2. The primary variable, vehicle gross weight, ranged from 5,000 to 250,000 lb (2,268 to 113,398 kg); see Figure 7. The sensitivity of each configuration to the design parameters was computed by varying each parameter while holding the other parameters constant at their baseline value. The results of the sensitivity analysis for main rotor disc loading are shown in Figure 8; number of main rotor blades, main rotor thickness ratio, main rotor solidity, main rotor tip speed, main rotor blade attachment offset, engine maximum power, main rotor blade profile drag coefficient, and turbofan engine by-pass area ratio are shown in Figure 9; tail rotor radius ratio, tail rotor location, tail rotor solidity, tail rotor tip speed, number of tail rotor blades, tail rotor blade attachment offset, and tail rotor blade profile drag coefficient are presented in Figure 10.

DISCUSSION

Results of the LPS weight analysis (Figure 7) indicate that tip-driven rotor systems have an LPS weight advantage over both single and tandem rotor helicopters for all vehicle gross weights. This result was not unexpected, because the tip-drive concept eliminates a major component whose weight is not offset by the increases in powerplant and controls weights. The result that the tandem rotor system had lower LPS weights than the single rotor for all vehicle gross weights was unexpected and counter to experience, which has shown that the single rotor

is superior at low vehicle gross weights. (The gross weight beneath which the single rotor drive system weighs less is difficult to define.)

The weight trend equations (or any trend equations, for that matter) must be used judiciously. The equations, in general, have been developed from data for vehicles with different designs and missions, and often with subtly different characteristics. The sophistication of the equations varies from a few easy-to-define parameters to many difficult-to-determine parameters. Trend equations are really accurate only within the range of the original data base, and extrapolation can often give misleading results. For example, increasing vehicle gross weight by a factor of four from 50,000 to 200,000 lb (22,680 to 90,718 kg), while holding geometry and loading parameters constant, results in a difference of 30 percent between the rotor blade weights predicted using the Hughes Aircraft and Boeing Vertol trend equations. (Both blade weight trend equations were developed using some of the same helicopters.) Because the rotor blades account for about 25 percent of LPS weight, which is about 25 percent gross weight for a 200,000-lb (90,718-kg) helicopter, a 30-percent shift in blade weight amounts to about 2 percent of gross weight (a sizable fraction of potential payload).

Trend equations, unfortunately, are the only means--short of detailed design--to estimate weights. Because the trend equations are applied well beyond the range of available data, the results should be used only qualitatively to compare the three configurations. The conservatism of the tip-drive weight prediction, as shown in Figure 9, may be sufficient to offset any possible inaccuracy caused by comparing two different sets of trend equations.

The mission application envisioned for a very heavy lift helicopter is the short-range transport of a 120,000-lb (54,431-kg) payload. A helicopter capable of this mission would have a gross weight of 200,000 lb (90,718 kg), or more.

The computed LPS component weights for 200,000-lb (90,718-kg) helicopters (Table 3) allow an appreciation of the size of the proposed vehicle, for example, the rotor blades each weigh about 4,000 lb (1,814 kg). For the shaft-driven helicopters, the main rotor drive system and main rotor blades are the heaviest components; for the tip-driven helicopter, the main rotor blades and main rotor controls are the heaviest. Considering the massive size of the blades, it is understandable that the main rotor controls are also massive.

The circulation control concept presents the option of eliminating mechanical cyclic pitch by substituting pneumatic cyclic lift. Thus, CC application should result in a considerable weight savings through removal of the cyclic pitch actuators. These actuators of necessity must be very large to move the blades at the required frequency and to absorb the blade dynamic and aerodynamic loads. Figure 11 illustrates the full weight savings potential of CC applied to the tip-driven rotor by assuming that the main rotor controls weight approaches zero. The potential savings range from 19 percent of the LPS for a tip-driven rotor to about 11 percent for shaft-driven rotors (as calculated from Table 3 for 200,000-lb (90,718-kg) helicopters). Application of circulation control presents a significant opportunity for LPS weight reduction.

The sensitivity analysis indicates that none of the three baseline designs is optimized with regard to LPS design parameters. The parameter having the strongest influence on the LPS weight of all configurations is disc loading, as shown in Figure 8. As indicated, a 10-percent increase in disc loading would yield about a 2-percent gross weight decrease in LPS weight.

Disc loading is not an unrestricted parameter. Some factors that influence the selection of a disc loading value are mission and landing area. Missions including extended hover requirements are best met by vehicles with low disc

loadings because of their high efficiency in hover. Missions with high speed cruise and short duration hover requirements are best met by high disc loading helicopters because of the lower empty weight and high cruise efficiency.

Landing area conditions place a maximum value on disc loading. The high downwash velocity associated with high disc loading cannot be tolerated where erosion or danger from flying objects is a factor or near personnel work areas. The highest disc loading on a current United States helicopter is about 15 lb/ft^2 (718 Pa), which under good, hard surface conditions is considered to be about the limit where personnel are concerned.

Of the remaining main rotor parameters (Figure 9), the number of blades for shaft-driven helicopters and solidity for tip-driven helicopters are as important as disc loading. Decreasing the number of blades by one or solidity by 10 percent would result in LPS reductions of about 2 percent of gross weight. The other main rotor parameters yielded variations of less than 1 percent of gross weight for a 10-percent variation of the parameter. In all cases, tail rotor parameters yielded variations of less than 0.1 percent of gross weight for a 10-percent variation of each parameter from its baseline value. The effect of tail rotor parameters on LPS weight is small because the tail rotor components make up only about 2 percent of LPS weight.

The sensitivity analysis indicates that each configuration may be improved with regard to LPS weight by changing the main rotor parameters, especially disc loading, number of blades, and solidity.

RESULTS

Analysis of helicopter useful load trends indicates that tip-driven rotors have a higher potential for achieving useful loads in excess of 60,000 lb

(27,216 kg) than single or tandem rotor shaft-driven helicopters. In addition, the tip-driven rotor has lower lift-propulsion system weight than either of the two shaft-driven alternatives.

The sensitivity analysis identifies disc loading, number of blades, and solidity as equally important in determining LPS weight.

a. Decreasing disc loading by 10 percent increases LPS weight by about 2 percent of gross weight.

b. For shaft-driven rotors, decreasing the number of blades by one decreases LPS weight by about 2 percent of gross weight.

c. For tip-drive rotors, decreasing solidity by 10 percent decreases LPS weight by about 2 percent of gross weight.

d. For a given configuration, tail rotor parameters have relatively insignificant effect on LPS weight.

An extensive investigation of the impact of circulation control on very heavy lift helicopters was not conducted; however, the results indicate that circulation control has the potential to decrease the LPS weight by as much as 19 percent.

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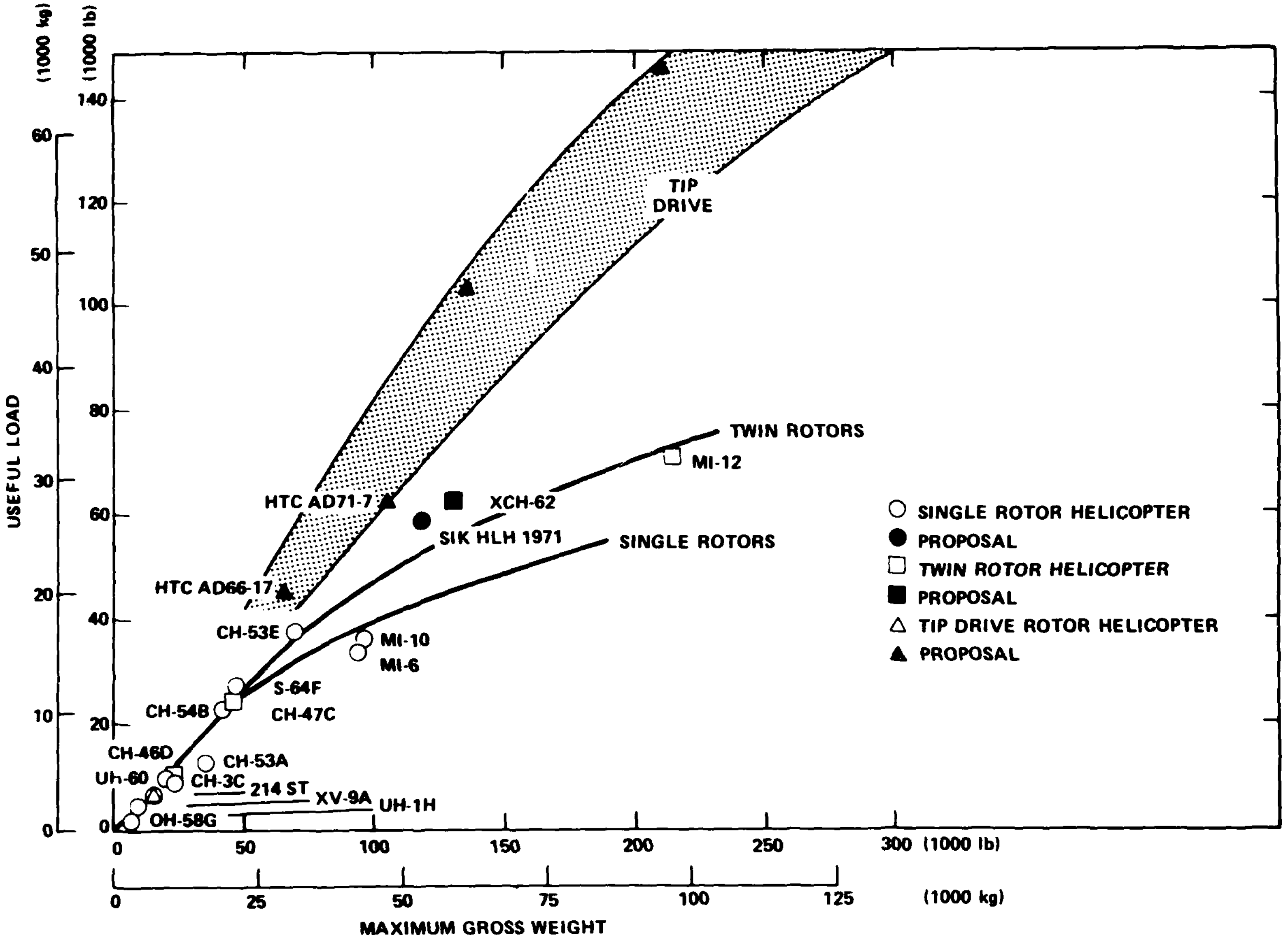


Figure 1 - Helicopter Useful Load Trends

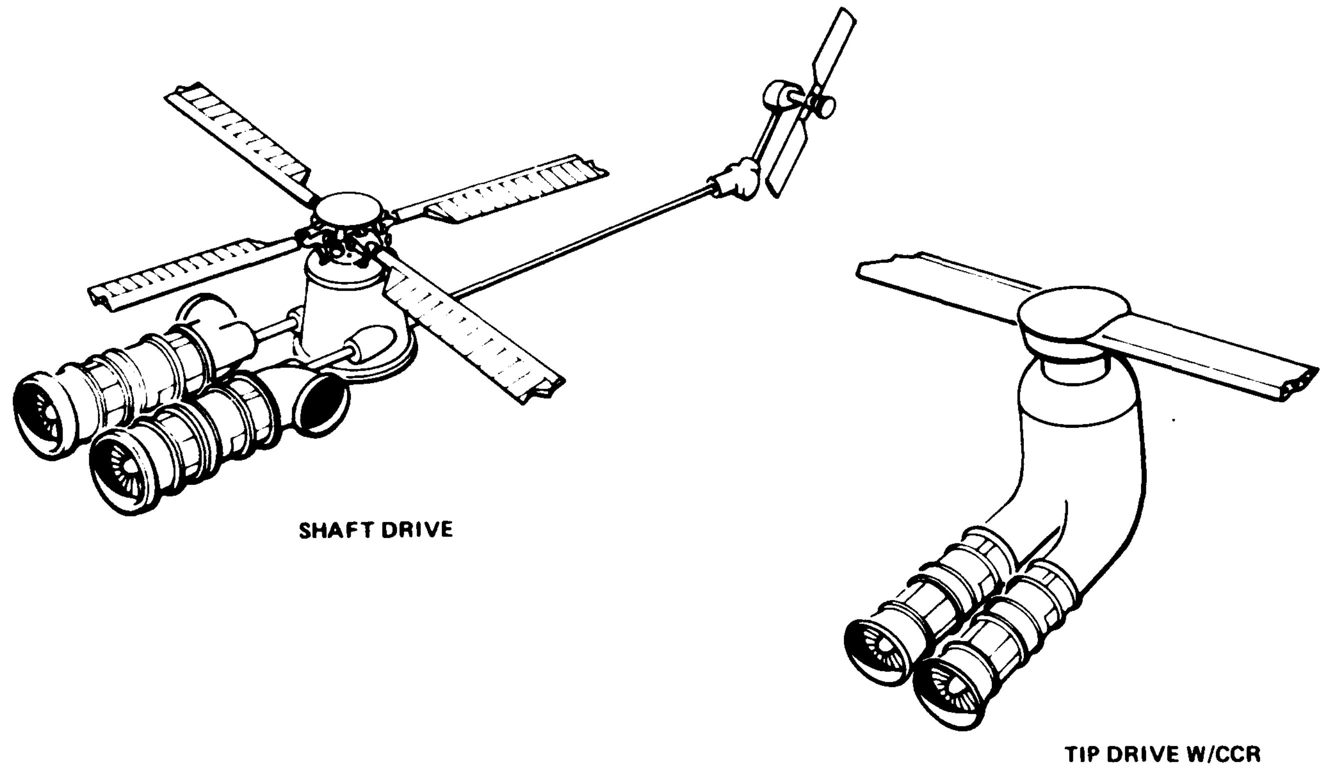


Figure 2 - Single Rotor Configuration Comparison

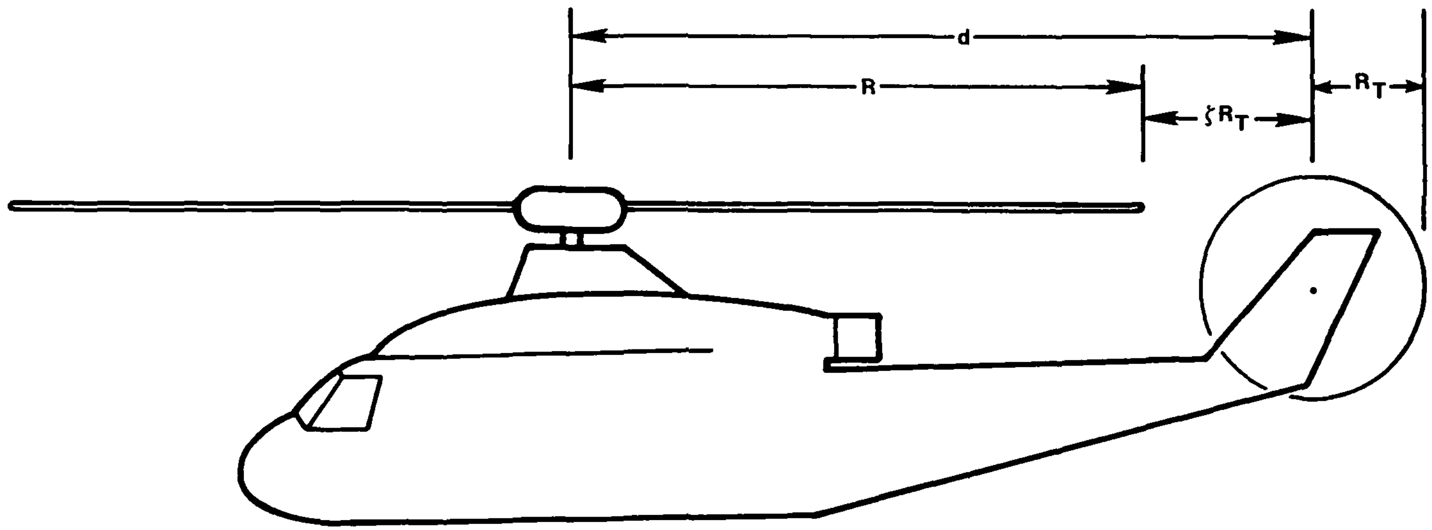


Figure 3 - Tail Rotor Location Parameter

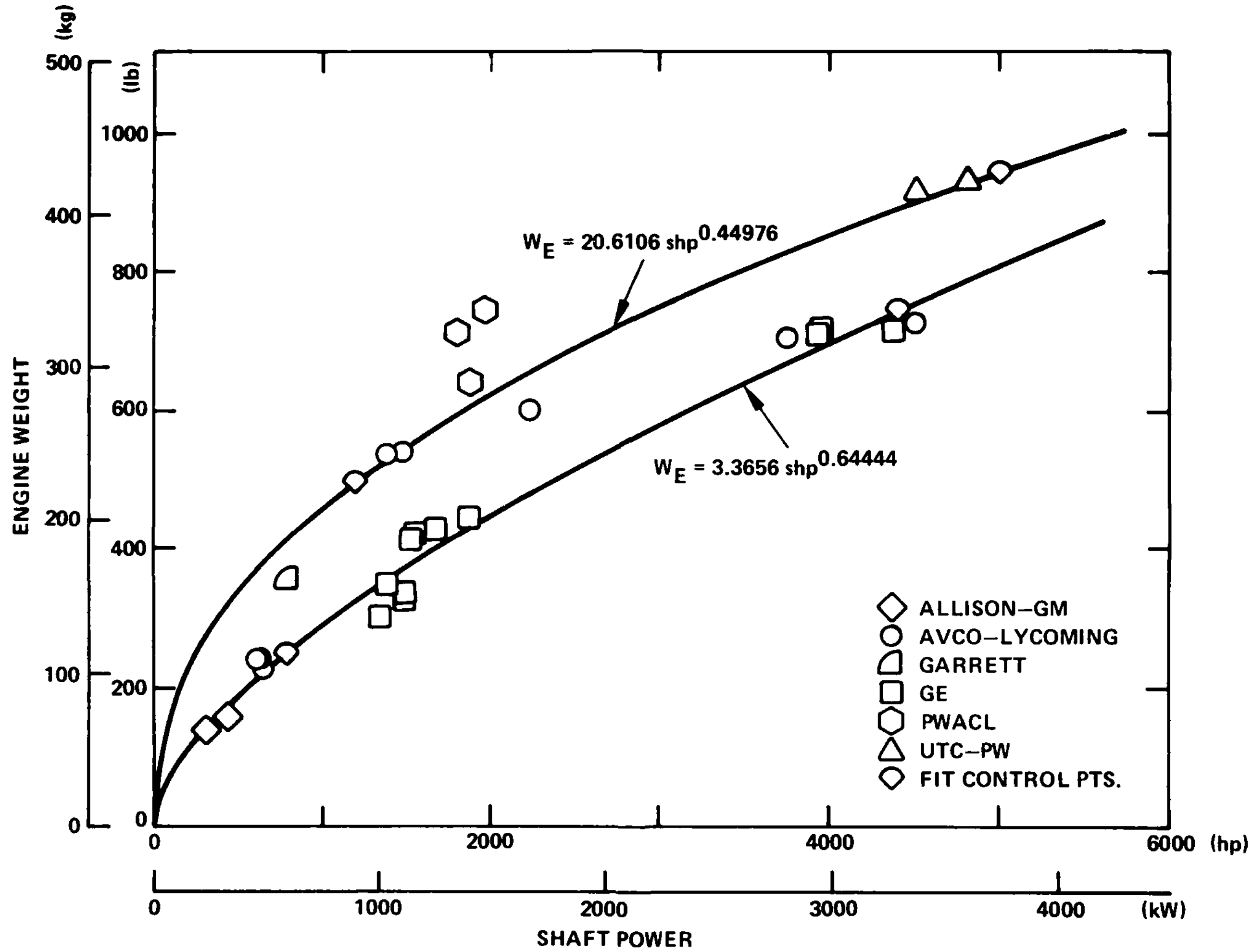


Figure 4 - Turboshaft Engine Weight Trends

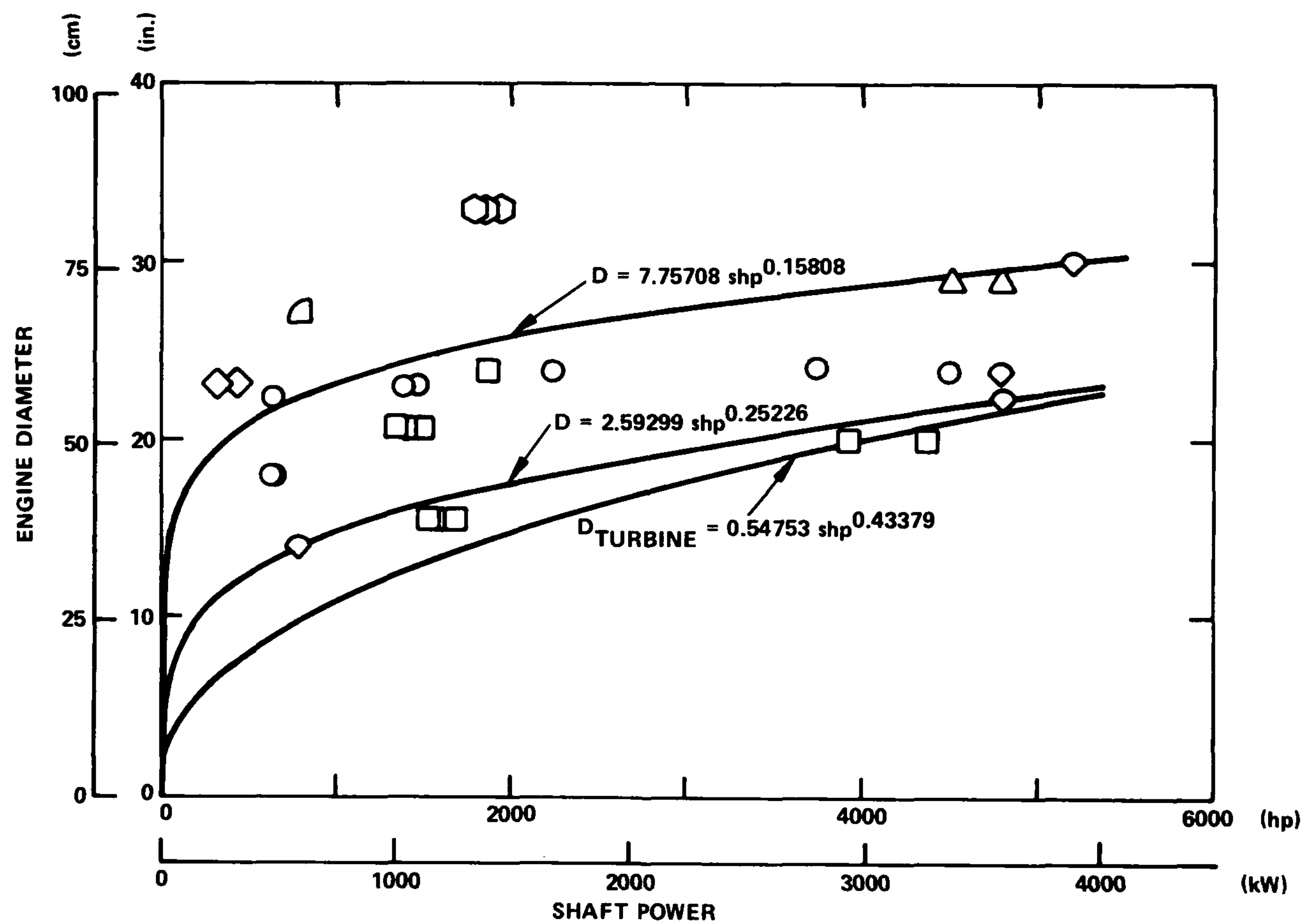


Figure 5 - Turboshaft Engine Diameter Trends

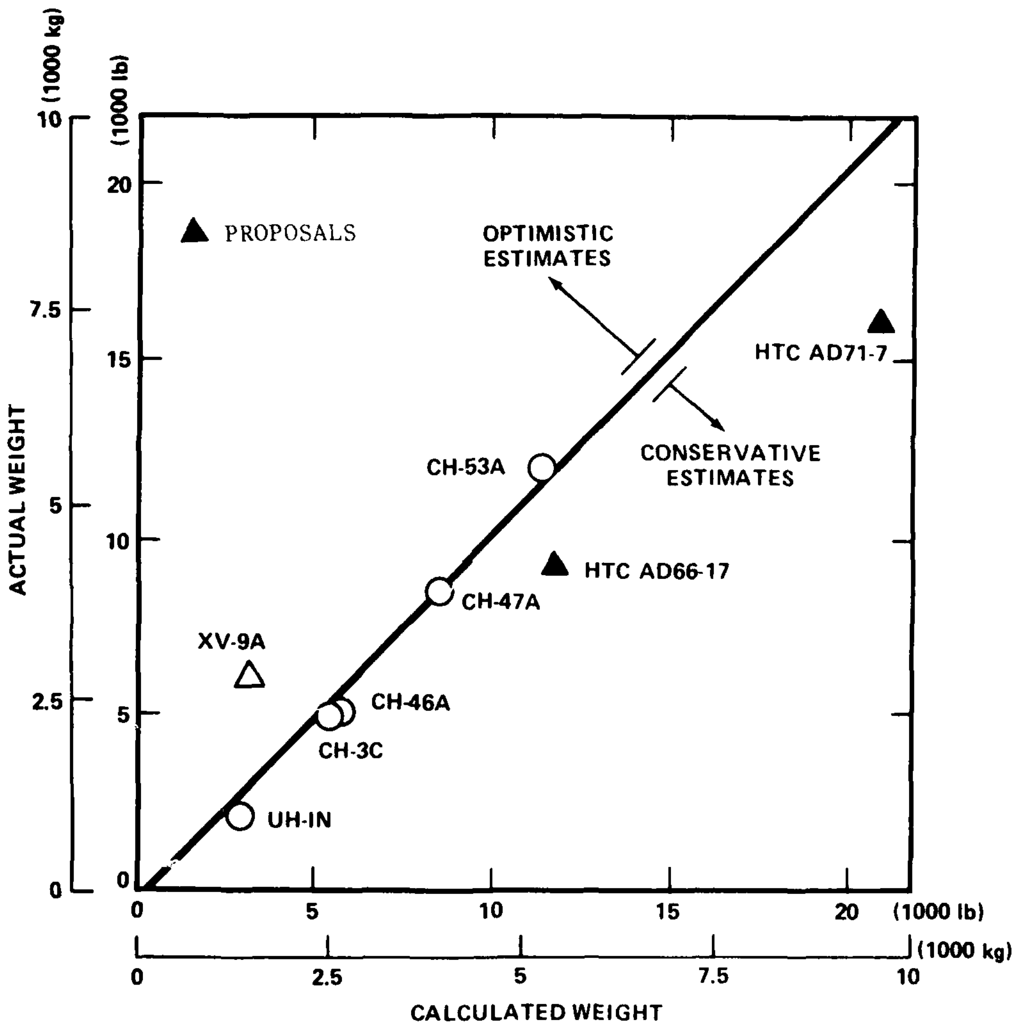


Figure 6 - Lift-Propulsion System Weight Correlation

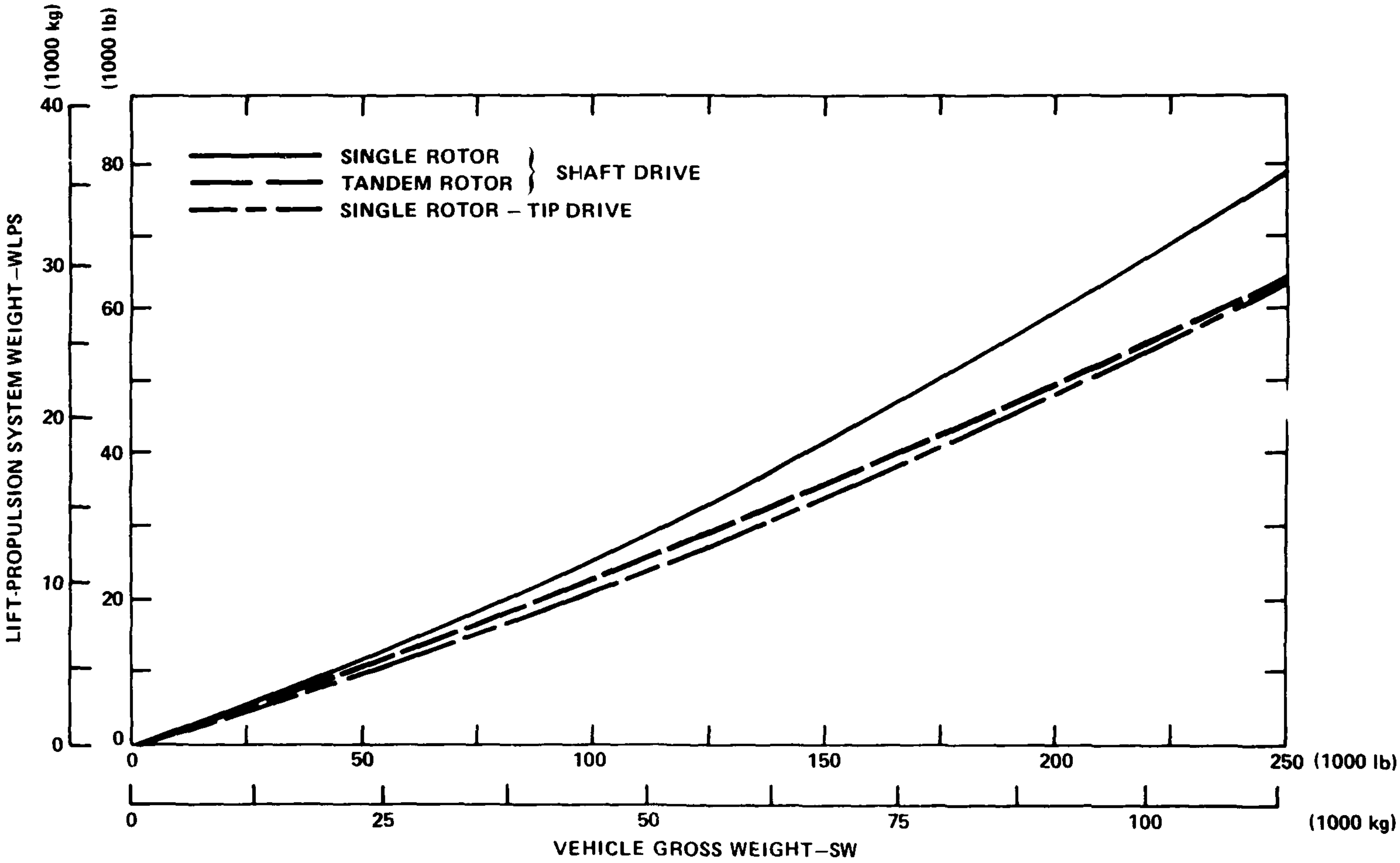


Figure 7 - Lift-Propulsion Svstem Weight Trends

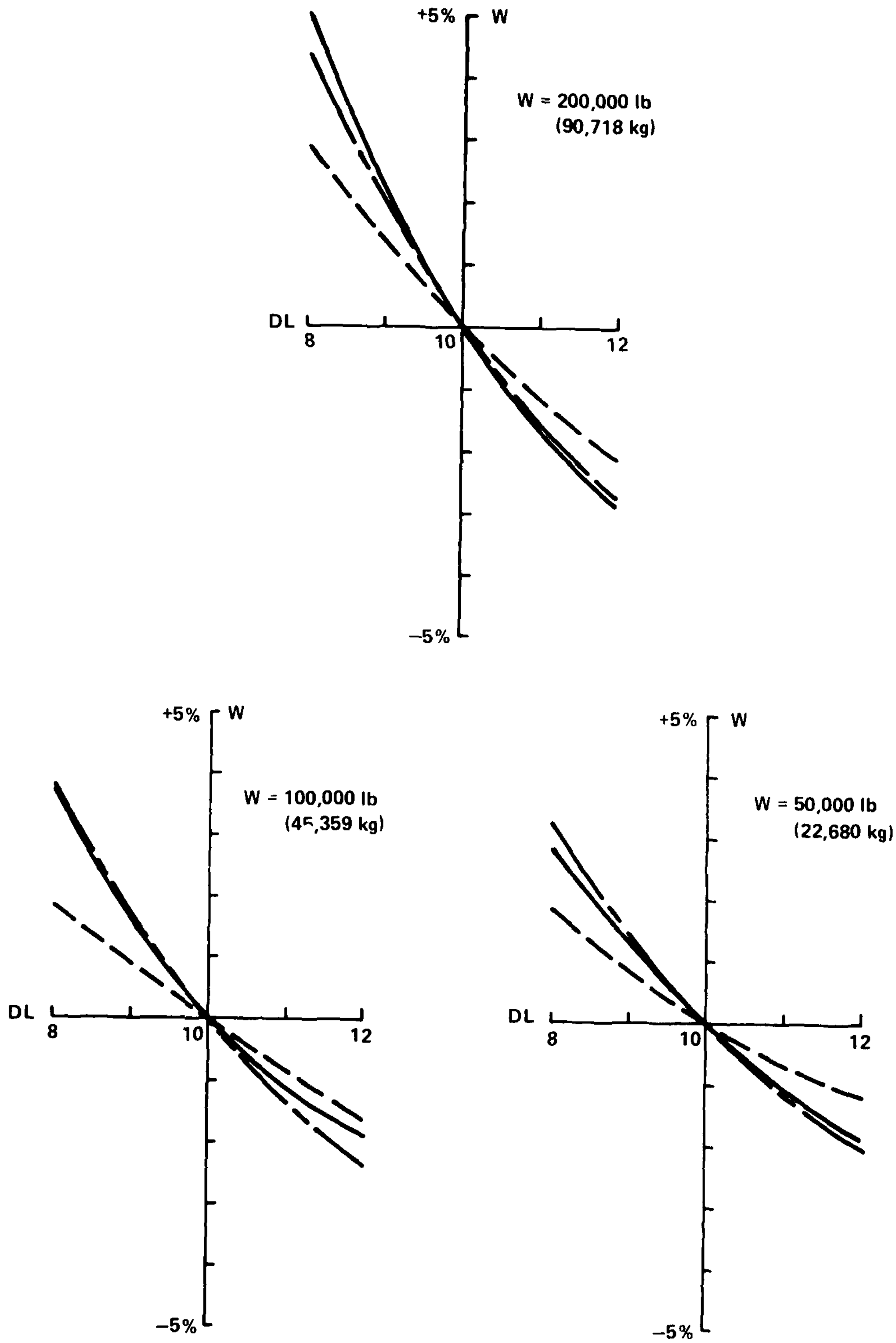


Figure 8 - Lift-Propulsion System Sensitivity to Disc Loading

Figure 9 - Lift-Propulsion System Sensitivity

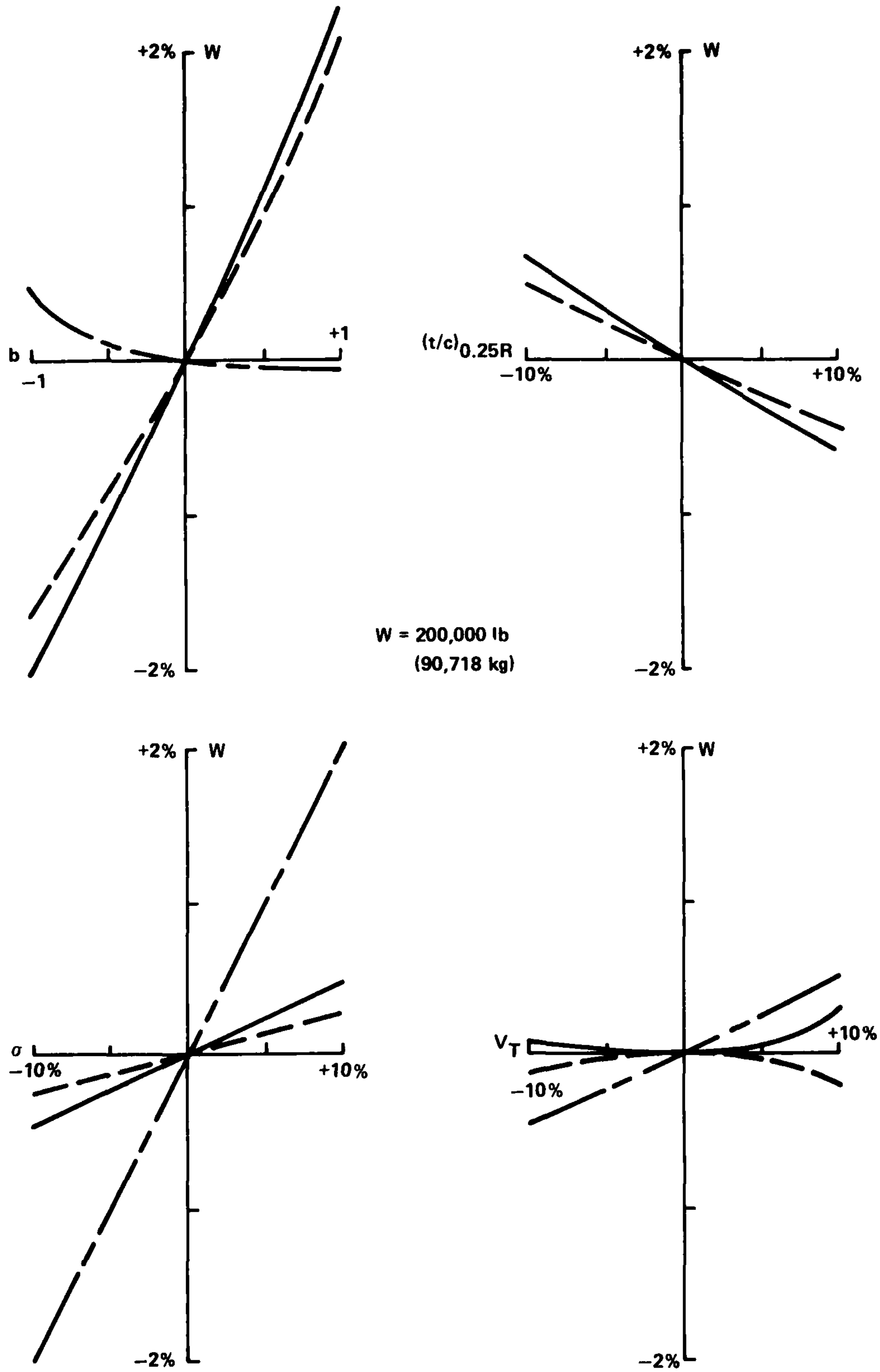


Figure 9 (Continued)

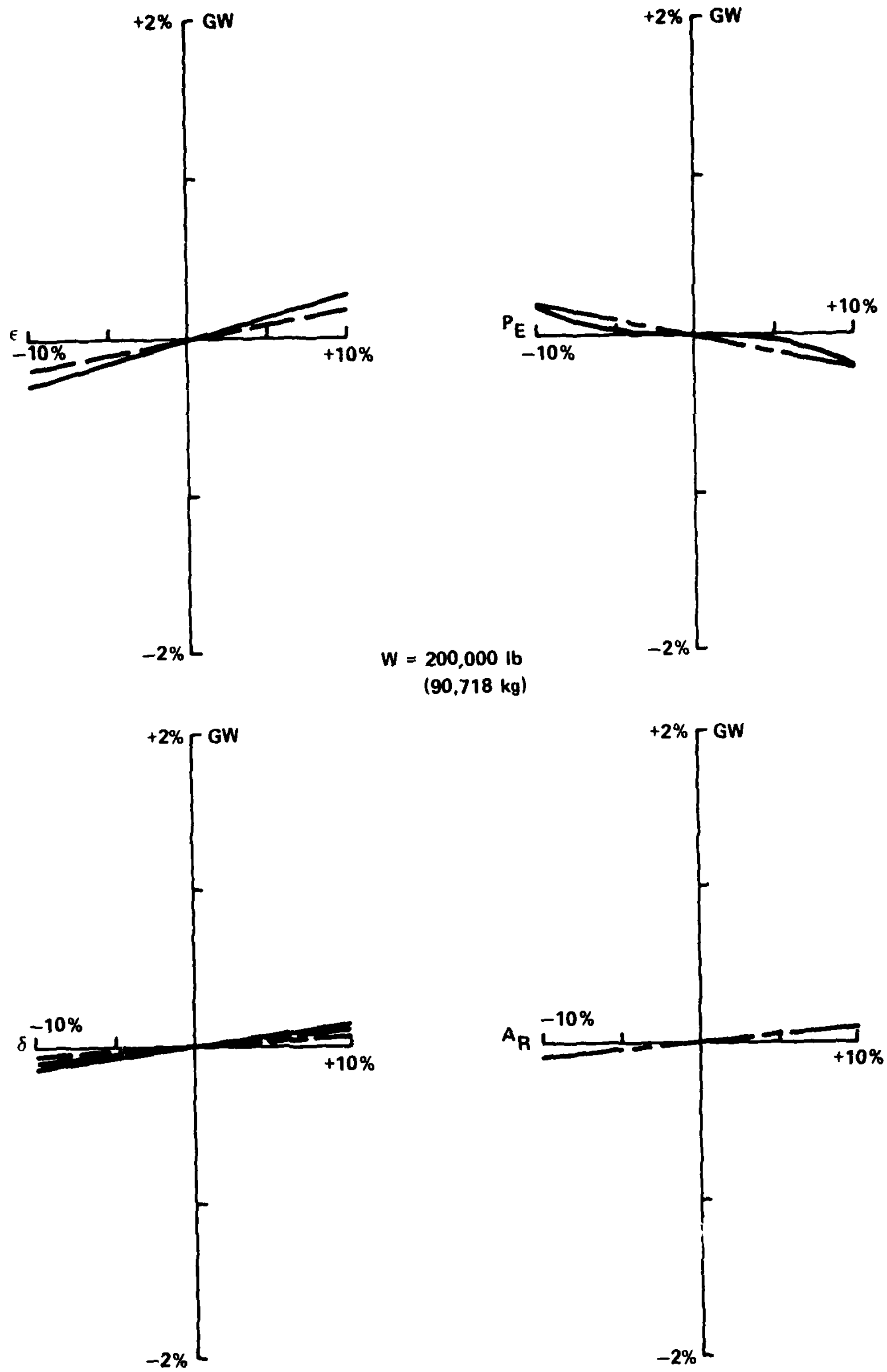


Figure 10 - Lift-Propulsion System Sensitivity to Tail Rotor Parameters

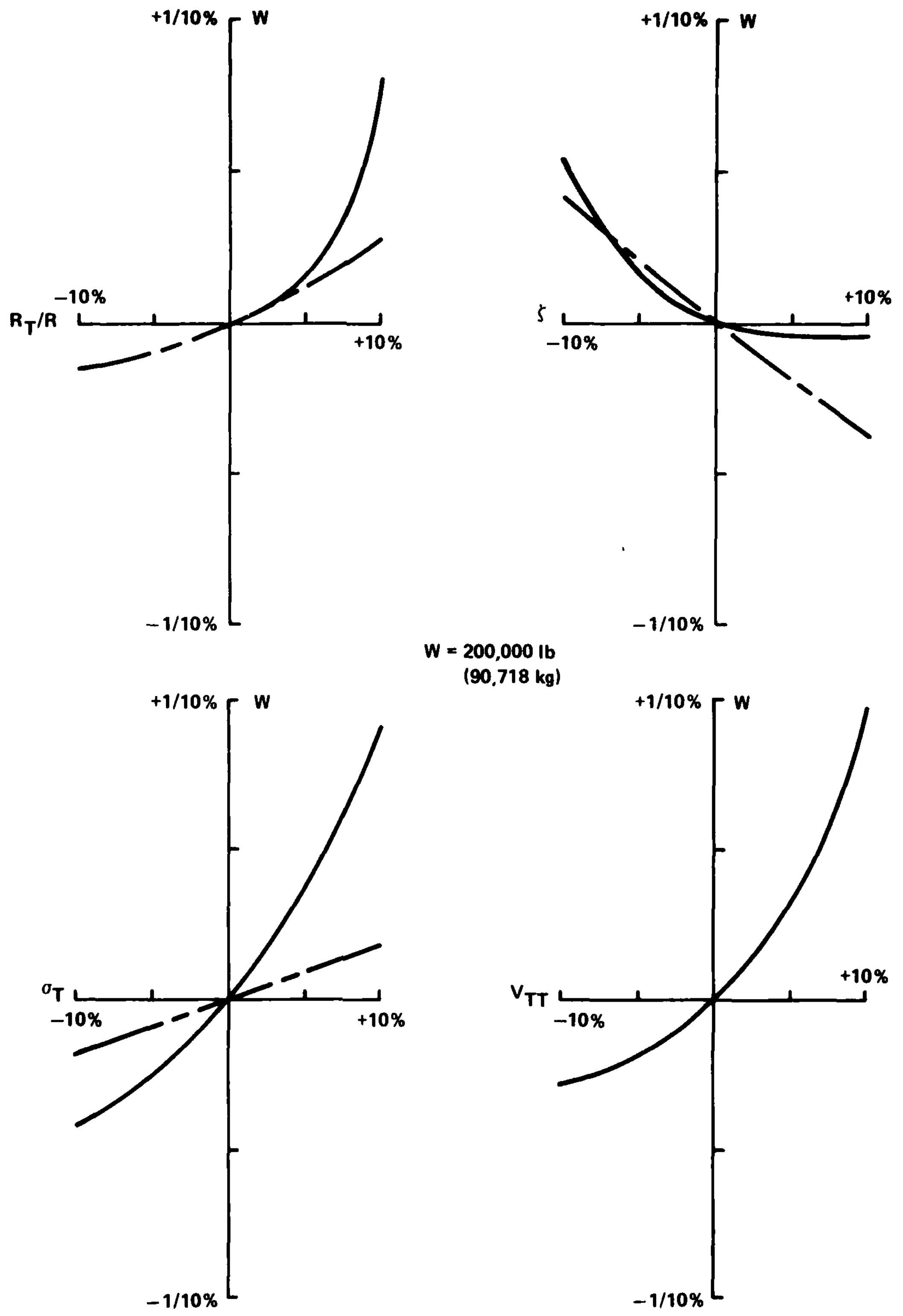
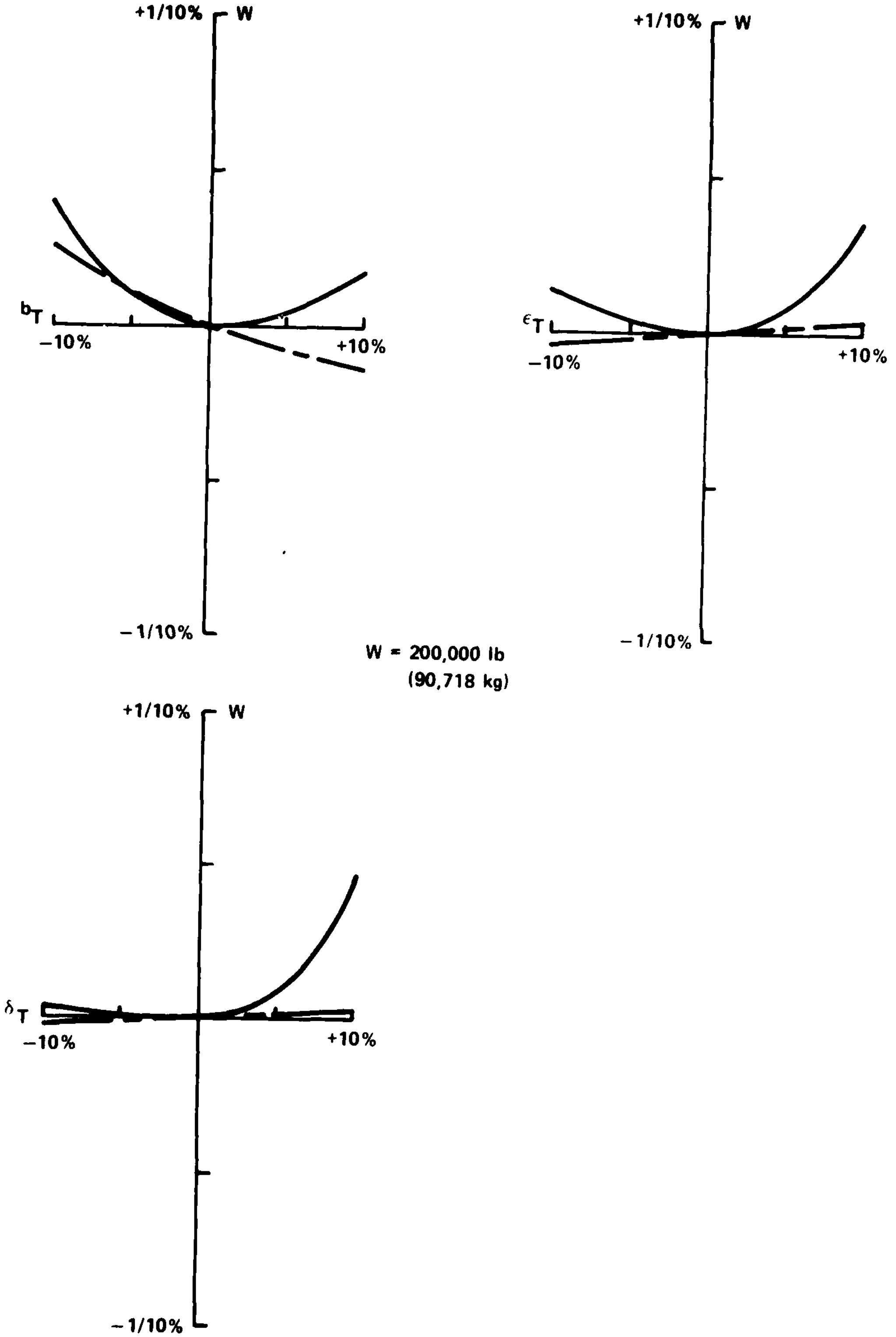


Figure 10 (Continued)



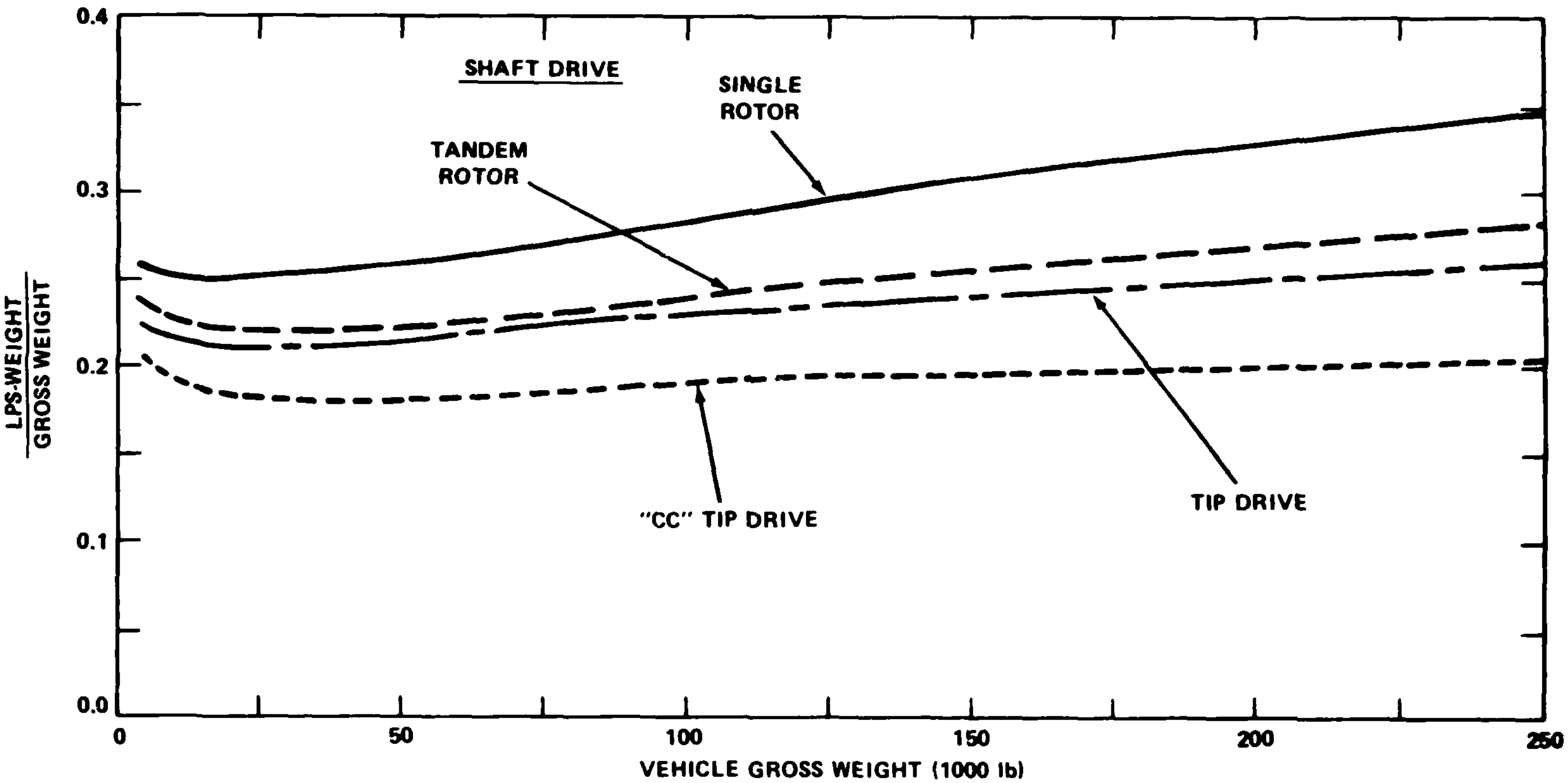


Figure 11 - Lift-Propulsion System Weight Fractions

TABLE 1 - HELICOPTER DESIGN INPUTS

Input Parameter	Main Rotor	Tail Rotor
Number of Blades	x	x
Solidity	x	x
Tip Speed	x	x
Profile Drag Coefficient	x	x
Blade Attachment Offset	x	x
Thickness Ratio @ 0.25R	x	
Radius Ratio (R_T/R)		x
Tail Rotor Location Parameter		x
Minimum Number of Engines		
Maximum Shaft Horsepower per Engine		
Turbofan By-pass Area Ratio; Engine RPM		
Limit Load Factor		
Crash Load Factor		
Air Density		

TABLE 2 - CONFIGURATION DESCRIPTIONS

	Single Rotor Tip Drive	Single Rotor Shaft Drive	Tandem Rotor Shaft Drive
Main Rotor			
Number of Blades	4	4	3
Solidity	0.1098	0.0885	0.0619
Thickness Ratio @ 0.25 Radius	0.1500	0.1200	0.1200
Blade Hinge			
Attachment Offset (%R)	17.470	8.4000	6.5000
Parasite Drag Coefficient	0.0102	0.0098	0.0100
Tip Speed (ft/sec)	700.00	750.00	710.00
Tail Rotor			
Number of Blades	4	4	-
Solidity	0.3330	0.1420	-
Blade Attachment Offset (%R)	10.000	10.000	-
Parasite Drag Coefficient	0.0098	0.0098	-
Tip Speed (ft/sec)	700.00	750.00	-
Radius Ratio	0.0709	0.2097	-
Location Factor	-3.6700	1.1012	-
Powerplant			
Minimum Number of Engines	2	2	2
Maximum Horsepower per Engine	7000.0	7000.0	7000.0
By-pass Area Ratio	0.9000	-	-
Engine RPM	-	-	-
Load Factors			
Limit	2.5000	2.5000	2.5000
Crash	8.5000	8.5000	8.5000
Air Density	0.002378	0.002378	0.002378
Technology Factors			
Developed Steel Rotor Hubs	x	x	x
Articulated Folding Blades	x	x	x

TABLE 3 - ESTIMATED LPS COMPONENT WEIGHTS FOR 200,000-POUND GROSS WEIGHT HELICOPTERS

(Weight in Pounds)

Component	Tip Driven Single Rotor	Shaft Driven Single Rotor	Shaft Driven Tandem Rotor
Main Rotor			
Blades	15,798	17,195	12,038
Hub(s) and Hinges	7,639	8,098	6,651
Fold Mechanism	4,500	4,806	3,177
Controls	9,632	8,583	5,534
Drive System	3,471	19,565	21,217
Tail Rotor			
Hub and Blades	473	1,332	-
Drive System	546	1,031	-
Engines	7,359	3,953	4,559
Engine Mounts	292	163	197
	49,710	64,726	53,373

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